# 10 Years of Florida-Bitter Magnet Technology

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10 years ago, on March 18, 1995 the world's first Florida-Bitter magnet (Figures 1 and 2) successfully reached its design field of 30 T at the NHMFL in Tallahassee, Florida. This magnet marked a world record, and with it, a major milestone in the development of resistive magnet technology. It showed that the NHMFL had taken leadership on an international scale by generating much higher fields with resistive magnets than the other magnet laboratories, and was even competing successfully with their sophisticated hybrid magnets. The new technology, invented and developed to technical maturity at the NHMFL, has demonstrated its superiority. It has since become the international standard for high-field dc systems, adopted by most of the world's large dc field facilities.

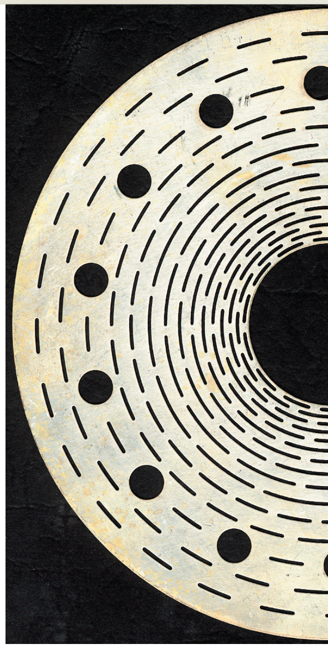


**Figure 1.** Conductor from first Florida-Bitter magnet, 30 T, 1995, NHMFL. Note heavily elongated cooling holes in a staggered grid.

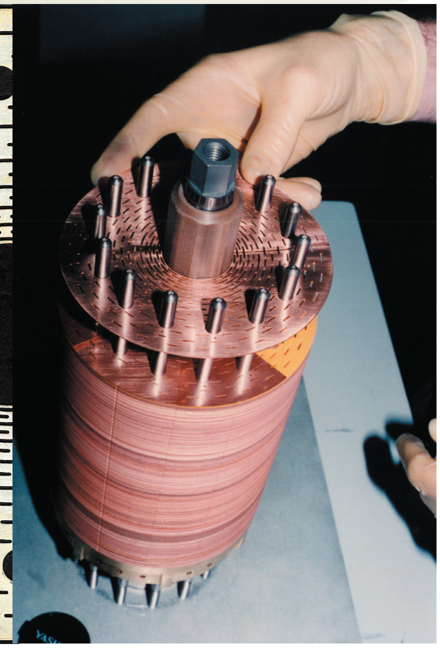


**Figure 2.** Stacking the innermost coil of first Florida-Bitter magnet, 30 T, 1995, NHMFL.

On the road to higher fields, there were historically competing requirements the magnet designer would address: high-field magnets require high current densities that result in (a) high power densities and (b) high Lorentz body-forces. Introducing cooling holes introduces stress and current density concentrations that further raise stresses and power densities. Stronger materials typically have lower electrical conductivity, hence require more cooling holes. Magnet designers worldwide would trade-off strength versus conductivity and cooling.

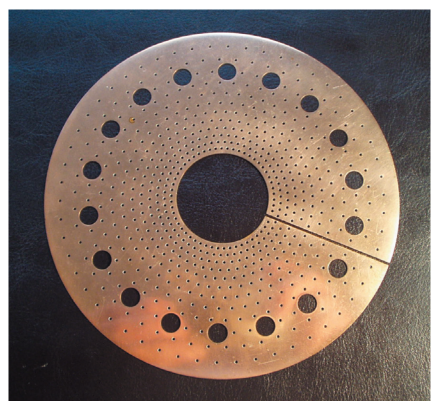


**Figure 3.** Bitter disk from 27 T magnet, 1994, NHMFL. Note round cooling holes.

At the time of the founding of the NHMFL in 1990, two of the most prominent high-field dc magnet labs were the FBNML at MIT in Cambridge, Massachusetts and the GHMFL* in Grenoble, France. Both labs used the traditional Bitter magnet technology first employed by Francis Bitter in 1936.[2] This technology had two major limitations, both of which were of a mechanical (or structural) nature. First, the mechanical stress in a high-performance disk was typically not uniform but was concentrated at the inner edge by a process called "radial force transmission". Second, the slits in the disks introduced stress concentrations. These two phenomena limited the peak fields attainable with 10 MW of power, the standard at that time.[1]

Consequently, both the FBNML and the GHMFL used more advanced technology for the innermost coils of their highest-performance magnets. The FBNML used radial-Bitter and monohelix magnets that had higher cooling efficiency and were less sensitive to plastic deformation than traditional Bitter magnets. This allowed them to employ higher strength (and lower conductivity) materials and run them into the plastic regime. The GHMFL used the polyhelix technology that eliminated radial force transmission and stress concentrations and allowed more precise optimization than traditional Bitter magnets. This enabled them to use higher conductivity (and

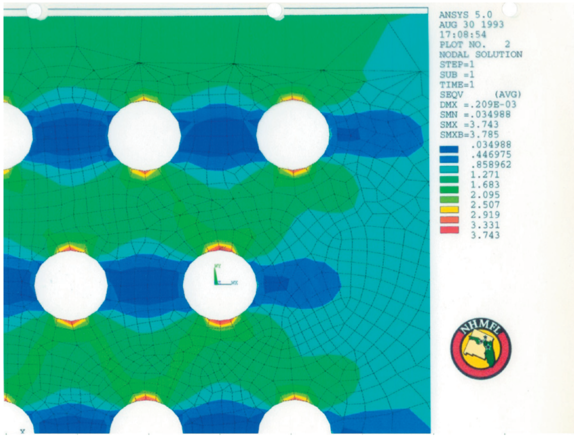



**Figure 4.** Stress distribution associated with round cooling holes. Peak value 3.7 times remote tension.

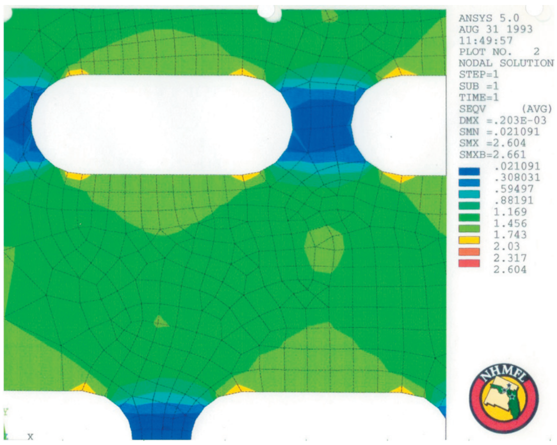



**Figure 5.** Stress distribution associated with elongated cooling holes. Peak value 2.0 times remote tension.

lower strength) materials and operate in the elastic regime with long fatigue life.

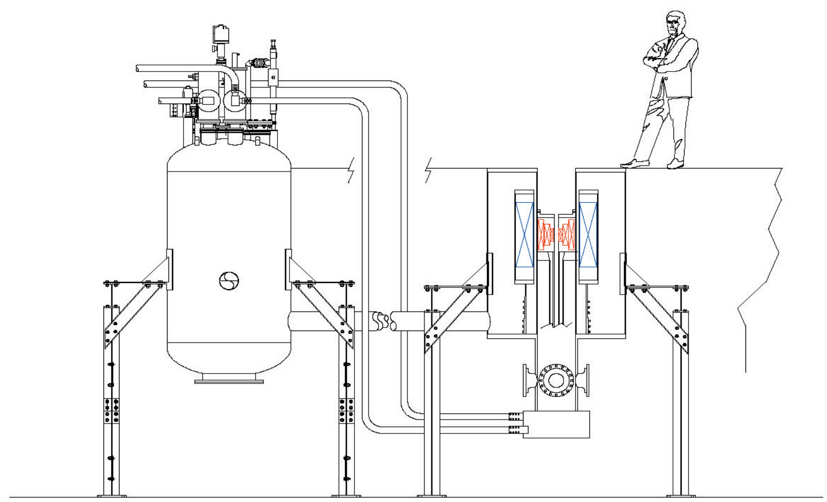
When initiating the development of resistive magnets at the NHMFL, we needed to build a shop, hire and train personnel, create a supply chain, and deliver the first reliable working system in about a year and a half. We decided the first magnet would use the simple, reliable Bitter magnet technology, but we fully intended to develop better technology for future systems. As we were designing the conductors for this first magnet, it was clear that greater efficiency could be attained by optimizing the shape and positioning of the cooling holes.[3,4,5] Time constraints and cost concerns, however, led to the design shown in Figure 3 employing traditional, round cooling holes.

In developing the second magnet at the NHMFL, more attention could be devoted to improving the magnet technology. Figures 4 and 5 present stress contours for two different arrays of holes with remote uni-axial tension. Figure 4 represents a hole-pattern very similar to that used in the 27 T magnet. We see that the peak stress near a hole is 3.7 times the maximum remote tension. Figure 5 represents a hole-pattern that uses the same hydraulic diameter and space factor but, by using elongated holes, the peak stress is only 2.0 times the maximum remote tension.[5] Thus, by employing heavily elongated cooling holes, peak stresses can be reduced by nearly 50%.

In addition, if one employs heavily elongated cooling holes in a Bitter magnet, the way one chooses to arrange those holes can also have a dramatic effect on the overall stress state in the coil. By staggering the consecutive rings of cooling holes, the various rings of conductor become nearly mechanically independent of each other. This drastically reduces the radial force transmission, similar to the independent coils of a polyhelix magnet. The resulting design using highly elongated holes in a staggered grid is called a Florida-Bitter magnet and results in average stresses as low as half that of a traditional Bitter magnet.[6] Indeed, the stress in a Florida-Bitter disk can be as much as 22% lower[1] than that in a (hypothetical) disk without any cooling holes at all!

**Figure 6.** 45 T Hybrid: device, insert disks, and a few of the personnel.

**Figure 7.** Schematic of proposed Series-Connected Hybrid at NHMFL. Resistive insert will employ Florida-Bitter technology.



Thus, with the Florida-Bitter technology, we reject the logical "or" and embrace the illogical "and". We choose both effective cooling and low stress!

In addition, the technology leads to high-field magnets consisting of a few stacks of identical disks. Each stack can operate within the elastic regime resulting in a long lifetime. This combination of mass-produced parts operating at modest stress levels results not only in exceptional performance, but also in low life-cycle costs.

Since its introduction in 1995 at the NHMFL, the Florida-Bitter technology has been adopted by four of the five largest dc field facilities worldwide. In addition to six designs in Tallahassee, the NHMFL developed a 30 T magnet for the Tsukuba lab in 1997 and some 33 T magnets for the Nijmegen lab in 2003.[1] In addition, the Sendai lab developed their own hybrid insert using Florida-Bitter technology achieving 30 T in 1999.[7] Finally, the Tsukuba lab completed two Florida-Bitter hybrid inserts (32 and 52 mm bores) in 1999 reaching a record dc field of 37.3 T.[8]

Presently, there are three new Florida-Bitter magnets being fabricated at the NHMFL. A 32 T, 50 mm magnet should be complete in April 2005. A 35 T, 32 mm system is due in the third quarter of 2005 and a 28 T, 32 mm system with high homogeneity is due in the fourth quarter of 2005.

Furthermore, a split resistive magnet is in development at the NHMFL that will likely employ the Florida-Bitter technology, or a new variation thereof. Finally, in July 2004 the NHMFL received funding for the first phase of a new Series-Connected Hybrid magnet project that will employ the Florida-Bitter magnet technology for the resistive insert (Figure 7).

The continuing success of the Florida-Bitter magnet technology is the product of a team of very talented, highly-motivated people, too numerous to list here, who were recruited to the NHMFL by Jack Crow, Hans Schneider-Muntau, and others. The author is greatly indebted to the various persons who have contributed to the success of the program. The author also gratefully acknowledges the editorial comments provided by Hans Schneider-Muntau and Kathy Hedick.

*The GHMFL did not officially adopt this acronym until a few years later.

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